STUDY OF PROCESS TECHNOLOGY FOR GaAlAs/GaAs HETEROFACE SOLAR CELLS

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SUMMARY

Process technology for producing 10,000 single-crystal GaAℓAs/GaAs solar cells per year was studied. The only technique that is presently developed to the point that 10,000 cells could be produced in one year is the infinite melt liquid phase epitaxy process. The lowest cost per cell is achieved with the advanced metal organic chemical vapor deposition process. Molecular beam epitaxy is limited by the slow growth rate. The lowest cost for an 18-percent efficient cell at air mass zero is approximately $70 per watt.

INTRODUCTION

This study of process technology assumes a requirement for 10,000 2 cm x 2 cm single-crystal pGaAℓAs/pGaAs/n-GaAs heteroface solar cells per year. For the purpose of this study, the processes evaluated for fabricating these solar cells are liquid phase epitaxy (LPE), chemical vapor deposition (CVD), and molecular beam epitaxy (MBE). Each of these processes utilizes an n-GaAs single crystal substrate approximately 250 μm thick on which the epitaxial layers are grown. Two LPE processes are considered: the infinite melt process and the finite melt process. In the infinite melt process, two separate reusable melts are maintained. One 5-kg melt of Ga, As, and the n dopant is used to grow an n-GaAs buffer layer on the substrate wafer. A second 3-kg melt of Ga, As, Aℓ, and the p-dopant is used to grow the p-GaAℓAs window layer. During the growth of the p-GaAℓAs, the p dopant diffuses into the buffer layer, forming the p-GaAs. In the finite melt LPE process, the smaller melts are not reused. One finite melt LPE technique, however, does not require the growth of the n-GaAs buffer layer. This method uses an etch back epitaxy process. The CVD process considered utilizes organometallic compounds of Ga, Aℓ, and AsH_3 for the gallium, aluminum, and arsenic sources. These compounds react on the surface of the heated substrate to form the GaAs and the GaAℓAs. In the MBE process, molecular beams of Ga, As, and Aℓ are directed from effusion cells onto a heated GaAs substrate in an ultrahigh vacuum such that the GaAs and GaAℓAs are formed. The MBE technique is characterized by slow growth rates (typically 1 μm per hour); however, the uniformity and composition of the layers are very precisely controllable. Growth rates for the CVD process are approximately 0.25 μm/min, and for the LPE process approximately 0.5 μm/min.

Substrates

Common to all these processes is the need for 250-μm thick single-crystal GaAs substrates. Considering saw kerf losses, polishing losses, and cleavage losses, annual production of 10,000 2 cm x 2 cm cells would require 15.1 kg of Ga and 16.2 kg of As, and results in a purchase price of $5.00 for each of the polished substrates.

Major Costs

Table 1 shows the major direct costs per cell for growth of the epitaxial layer for 10,000 2 cm x 2 cm solar cells per year using the various processes. The costs per cell shown in this table do not include the $5.00 cost for each polished 2 cm x 2 cm substrates which is common to all processes. For the purpose of this study, percent yield is defined as the percent of the input material that is incorporated in the epitaxial layer. The lowest costs per cell are for the infinite melt LPE (IM-LPE) process and for the metal organic CVD (MO-CVD) process. Assuming an 18-percent cell at AMO, the cost for the IM-LPE process is $71 per watt including the substrate cost, and the cost for the OM-CVD process is $70 per watt including the substrate cost. From table 1, notice that the major items affecting the cost per cell for the epitaxial layer are the time to fabricate, the labor costs, and the capital equipment costs; however, the materials costs become important in some cases when the percent yield is lower than 100 percent. In no cases, however, are the energy costs a significant percentage of the cost per cell. Each of these items will now be discussed separately.

Fabrication Time

Table 2 shows the fabrication times for the various processes using one growth chamber of current design. From this table it can be seen that only the IM-LPE process can produce 10,000 cells per year using one growth chamber of current design. Table 2 shows that even if higher quality substrates were available such that no GaAs buffer layers were needed, a single MBE system could not produce the 10,000 cells in one year. The current MO-CVD systems in use are limited to growing one cell per cycle. The time to grow 10,000 cells is therefore 31 months. In order to grow the 10,000 cells in one year by this process, three systems would be required. A commercially available four-loop MO-CVD system can grow approximately 11 cells per cycle; therefore, this advanced system could produced the required cells in approximately three months. Scale-up of the MO-CVD process to produce 36 cells per cycle appears feasible. Thus, less than one month would be required to grow 10,000 cells using the most advanced system. Scale-up of the MBE process using a third-generation MBE system to produce about seven cells per run appears feasible; however, in order to use only two systems to produce 10,000 cells per year, the buffer layer must be eliminated.

Materials

Table 3 shows the material requirements for the 10,000 cells. The percent yield for the IM-LPE process is shown only at 100 percent since the use of all of the material removed from the confined melts is incorporated in the epitaxial layer. The MBE process is shown at a maximum percent yield of 50 percent since geometrical considerations would limit the percent yield to 50 percent. Additional experimental effort is needed to quantify the percent yield for the MO-CVD process and for the LM-LPE process; however, collection and recycling of the OM-CVD exhaust gases and the LM-LPE melts may be possible.

Labor Costs

Table 4 shows the labor costs for producing the required 10,000 cells. The three-month fabrication time for the MO-CVD process assumes the four-loop system. The 31-month fabrication time for the MBE process assumes a third-generation MBE system.

Capital Equipment

Table 5 shows the amoritized costs for the capital equipment. Note that the cost per cell is $0.42 for the IM-LPE process; however, the amortized cost per cell for advanced MO-CVD process is also low at $0.50 per cell.

CONCLUSIONS

Referring again to table 1, this study has shown that for producing 10,000 4-cm^2 GaAℓAs-GaAs heteroface solar cells per year, the lowest cost per cell is for the four-loop MO-CVD system with a 100-percent yield. The cost of cells produced by the MBE process is the highest for all processes studied; however, MBE is a useful tool for studying and optimizing solar cells. For both the MO-CVD process and the IM-LPE process, the substrate cost dominates the cost of the epitaxial layer. For both processes, the substrate cost is greater than 70 percent of the cell cost. Including the substrate cost, the lowest cost identified for GaAℓAs/GaAs heteroface solar cells is $70 per watt assuming 18 percent AMO efficiency.

● EXCLUDING OVERHEAD AND PROFIT

PROCESS	YIELD[1] (%)	TIME TO FABRICATE (MONTHS)	MATERIAL COSTS	UNBURDENED LABOR COSTS	CAPITAL EQUIPMENT COSTS	ENERGY COSTS	COST PER CELL[2]
LPE - INFINITE MELT	100	4	$ .006	$ 1.54	$ .42	$ .016	$ 1.98
- FINITE MELT	100	63	$ .006	$14.11	$ 2.67	$ .015	$ 16.80
	10	63	$ .06	$14.11	$ 2.67	$ .015	$ 16.86
	1	63	$ .62	$14.11	$ 2.67	$ .015	$ 17.42
MO-CVD	100	31	$ .23	$ 6.94	$ 5.17	$ .002	$ 12.34
	10	31	$ 2.29	$ 6.94	$ 5.17	$ .002	$ 14.40
	1	31	$22.94	$ 6.94	$ 5.17	$ .002	$ 35.05
	100	3	$ .23	$ 1.15	$ .50	$ .002	$ 1.88
	10	3	$ 2.29	$ 1.15	$ .50	$ .002	$ 3.94
	1	3	$22.94	$ 1.15	$ .50	$ .002	$ 24.59
MBE	50	344	$ .03	$77.06	$33.37	$3.95	$114.41
	5	344	$ .30	$77.06	$33.37	$3.95	$114.68
	50	31	$ .03	$ 6.94	$17.24	$ .36	$ 24.57
	5	31	$ .30	$ 6.94	$17.24	$ .36	$ 24.84

1. YIELD IS DEFINED AS THE RATIO OF THE MATERIAL IN THE EPITAXIALLY GROWN LAYERS TO THE MATERIAL INPUTTED TO THE PROCESS.
2. DOES NOT INCLUDE A $1.24/cm^2 PURCHASE PRICE FOR POLISHED SUBSTRATES.

Table 1: Summary of major direct costs per cell for growth of the epitaxial layers of 10,000 2-cm x 2-cm (AlGa)As/GaAs solar cells.

PROCESS	CYCLE TIME (HOURS)	NO. OF CELLS (2cm × 2cm)	TIME PER CELL (HOURS)	TIME FOR[1] 10,000 CELLS (MONTHS)
LPE - INFINITE MELT	2	32[2]	.06	4
- FINITE MELT	1	1	1.0	63
MO-CVD	0.5	1	0.5	31
	0.5	11	0.5	3
MBE - 11μm GROWTH	11	2	5.5	344
- 1μm GROWTH	1	2	0.5	31

1. BASED ON 160 HOURS OF OPERATION PER MONTH.
2. BASED ON A SYSTEM THAT HAS BEEN DEVELOPED TO SATISFY (LIMITED) PRODUCTION REQUIREMENTS.

Table 2: Summary of fabrication times for different epitaxial growth procedures using one growth chamber of current design.

- 250μm n-GaAs SUBSTRATE
- 10μm n-GaAs BUFFER LAYER
- 0.5μm p-GaAs LAYER
- 0.5μm p-(AlGa) As WINDOW LAYER

PROCESS	YIELD (%)	GALLIUM OR GALLIUM CONTAINING COMPOUND (g)	ARSENIC OR ARSENIC CONTAINING COMPOUND (g)
SUBSTRATE PREPARATION	17	15,084	16,210
LPE - INFINITE MELT	100	108	121
- LIMITED MELT	100	108	121
	10	1,080	1,212
	1	10,800	12,120
CVD - $Ga(CH_3)_3$	100	178	126
- AsH_3	10	1,779	1,261
	1	17,790	12,611
MBE - As/Ga = 10	50	216	2,424
	5	2,160	24,240

Table 3: Summary of material requirements to fabricate 10,000 2-cm x 2-cm GaAs solar cells assuming no recovery of lost material.

- ONE OR TWO FULL TIME OPERATING PERSONS AT $10.00 PER HOUR
- ONE PART TIME (20%) SUPERVISOR AT $20.00 PER HOUR

PROCESS	TOTAL TIME[1] (MONTHS)	NO. OF OPERATORS	TOTAL LABOR COST	LABOR COST PER CELL
LPE - INFINITE MELT	4	2	$ 15, 360	$ 1.54
- FINITE MELT	63	1	$141, 120	$14.11
MO-CVD	31	1	$ 69, 440	$ 6.94
	3	2	$ 11, 520	$ 1.15
MBE	344	1	$770, 560	$77.06
	31	1	$ 69, 440	$ 6.94

1. ASSUMING A SINGLE 8 HOUR SHIFT PER DAY.

Table 4: Summary of unburdened labor costs to grow epitaxial layers for 10, 000 (AlGa)As/GaAs solar cells with a single growth chamber.

● ASSUMING A FIVE YEAR DEBT AT 12% INTEREST

PROCESS	TOTAL CAPITAL EQUIPMENT COSTS	FABRICATION TIME (MONTHS)	TOTAL AMORTIZATION COST ALLOCATED TO SOLAR CELLS	AMORTIZATION COST PER CELL
LPE - INFINITE MELT	\$ 47,424[1]	4	\$ 4,219.68	\$ .42
- FINITE MELT	\$ 20,000	63	\$ 26,693.40	\$ 2.67
MO-CVD	\$ 75,000	31	\$ 51,718.23	\$ 5.17
		3	\$ 5,004.99	\$ .50
MBE	\$250,000	344	\$333,666.60	\$33.37
		31	\$172,394.47	\$17.24

[1] INCLUDES \$7,424.00 FOR 8,000 GRAMS OF MELT HELD IN INVENTORY IN TWO GROWTH CHAMBERS

Table 5: Summary of capital equipment amortization cost for different solar cell fabrication processes assuming a minimum number of growth chambers.